572

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Self-starting passively mode-locked fibre ring laser exploiting nonlinear polarisation switching

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Nonlinear birefringence effects in an all-fibre ring laser cavity have been exploited to produce self-starting passive mode-locking with pulse durations lying in the nanosecond region.

1. Introduction

Self-starting, passive mode-locking of erbium-doped fibre lasers (EDFL) has so far been demonstrated using the nonlinear characteristics of the Sagnac loop mirror [1,2] or a fast saturable absorber [3]. Nonlinear birefringence [4] has previously been exploited as a self-sustaining mechanism for passive mode-locking of fiber lasers [5], but, owing to the short interaction lengths and the relatively high birefringent fibres used, mode-locking could only be initiated by the use of an active modulator. Recent experimental evidence [6,7], backed by earlier theoretical predictions [8], has demonstrated the feasibility of polarisation switching in the multibeat-length regime. We report the use of this effect to produce passive, self-starting mode-locking in a 200 m fiber laser ring cavity generating stable square pulses at the round-trip frequency of 1 MHz. The pulse duration could be varied in a controlled manner from 2 to 10 ns by varying the pump power. By increasing the cavity length to 3 km extremely broad (150 nm) oscillating linewidths due to stimulated Raman scattering were observed.

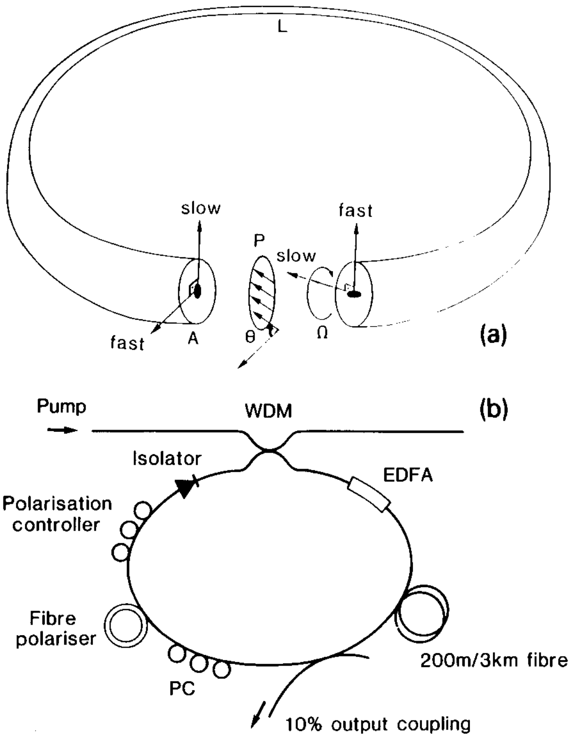

Fig. 1. (a) Conceptual cavity schematic. (b) Experimental set-up.

2. Theory

Consider a ring laser cavity which includes a birefringent element [L] a polariser [P] and a rotating element [Ω] as shown in fig. 1a. Starting from point A and representing [L], [P] and [Ω] with their Jones matrices we can write the following eigenvalue equation for the components of the electric field circulating inside the cavity:

$$[P][\Omega][L]\begin{bmatrix} E_f \\ E_s \end{bmatrix} = \lambda \begin{bmatrix} E_f \\ E_s \end{bmatrix}, \quad (1)$$

where the subscripts f and s denote that the electric field has been resolved with respect to the fast and slow axes of the birefringent element. The eigenvalues λ that obey eq. (1) are the following:

$$\lambda_1 = 0 ,$$

$$\lambda_2 = \exp(i\beta_f L)\cos(\theta - \Omega)\cos\theta + \exp(i\beta_s L)\sin(\theta - \Omega)\sin\theta , \quad (2)$$

where β_f, β_s are the two propagation constants along the axes of the birefringent element of length L, θ is the azimuth angle of the polariser with respect to the fast axis and Ω is the rotation angle. Note that the system possesses only one polarisation eigenmode because one of the eigenvalues is zero. The magnitude of the second eigenvalue gives the round trip intensity transmission T of the system:

$$T \equiv |\lambda_2|^2 = \cos^2\Omega - \tfrac{1}{2}\sin(2\theta)\sin[2(\theta - \Omega)] \times [1 - \cos(2\pi L/L_{b0})] , \quad (3)$$

where L_{b0} is the natural (linear) beat length of the birefringent element. Three cases are of particular interest:

(a) If $\cos(2\pi L/L_{b0}) = 1$, i.e. the ring is made up of an integer number of beat lengths at the wavelength of operation, then the round trip transmission is equal to $\cos^2\Omega$, i.e. independent of the orientation of the polariser θ.

(b) If $\cos(2\pi L/L_{b0}) = -1$, i.e. the ring is made up of a half integer number of beat lengths at the wavelength of operation, and $\Omega = 0$ then the transmission becomes equal to $1 - \sin^2(2\theta)$.

(c) If $\theta = 0$ then the transmission becomes wavelength independent.

The concept of nonlinear polarisation switching in optical fibres relies on the fact that the beat length of the fibre at a particular wavelength is power dependent. Winful [8] had first published a theoretical analysis of this effect which involves the use of elliptic functions and later Garth and Pask [11] derived approximate expressions which can be used in some particular cases. According to Winful, the beat length variation with power is given by

$$\frac{L_b}{L_{b0}} = \frac{2K(m)}{\pi[1 + p^2 - 2p\cos(2\theta)]^{1/4}} , \quad (4)$$

where L_b is now the new (nonlinear) value of the beat length, $K(m)$ is the quarter period of the jacobian elliptic function $\mathrm{cn}(x|m)$, θ is the azimuth angle of the polarised light with respect to the fast axis of the fibre and p is the optical power in normalised units:

$$p \equiv n_2 I / \tfrac{3}{2}\Delta n , \quad (5)$$

where n_2 is the nonlinear refractive index coefficient, I is the light intensity and Δn is the refractive index difference between the two birefringent axes. From Garth's paper an approximate expression to eq. (4) can be inferred in the case of linearly polarised input at $\theta = 45°$:

$$L_b/L_{b0} = (\tfrac{3}{8} + \tfrac{5}{8}\sqrt{1 + p^2})^{-1/2} . \quad (6)$$

The beat length variation with input power ultimately then results in an intensity dependent cavity transmission $T(p)$. Figure 2 shows the numerically evaluated cavity transmission $T(p)$ for $\theta = 45°$, 30° and 20° with $L/L_{b0} = 1$ and $\Omega = 90°$, so that $T(0) = 0$ at the wavelength of operation. Notice that $T(p)$ reaches a maximum value of 1 around $p = 2.5$ and then starts falling again. It is this particular "switching" characteristic that forces our mode-locked laser (described below) to produce square-shaped pulses, as they pass through such a switch without any losses. Provided that Ω is set so that the cavity loss is max-

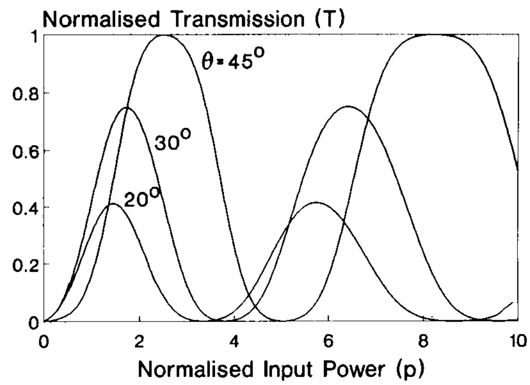

Fig. 2. Cavity transmission T versus normalised input power p for linearly polarised light at $\theta = 45$, 30 and 20 degrees to the fast axis and $\Omega = 90°$.

imised for low powers ($T(0)=0$) at a particular wavelength and θ is set equal to 45° (for maximum switching efficiency), we can use the approximate expression (6) and write the following equation for the "switching" power, i.e. the power required for $T(p)$ to reach its first maximum:

$$\left(\tfrac{3}{8}+\tfrac{5}{8}\sqrt{1+p^2}\right)^{-1/2}=\frac{2}{2+L_{b0}/L}, \qquad (7)$$

which has solution

$$p_{sw}=\sqrt{\tfrac{1}{25}\left(2(2+L_{b0}/L)^2-3\right)^2-1}\,. \qquad (8)$$

Figure 3 displays how the switching power p_{sw} depends on the number of beat lengths L/L_{b0} in the cavity. Notice that the p_{sw} has fallen drastically after 20 beat lengths, hence the advantage of working in the multi-beatlength regime. In terms of real power units, eq. (5) indicates that for the same number of beat lengths the use of low birefringent fibre provides an additional reduction to the optical power required in order to observe the nonlinear polarisation effects. In the experiments described below, we used 200 m of low birefringence spun fibre as part of a ring fibre laser cavity. This enabled nonlinear polarisation switching to take place at input pump powers as low as 80 mW.

3. Experimental

The experimental set-up is shown in fig. 1b. The pump source was an argon-ion pumped Ti:sapphire laser providing up to 3 W of cw light at 980 nm to pump the EDFL through a wavelength division multiplexing (WDM) coupler. The remaining output port of the WDM served for monitoring the launched pump power. The cavity of 4 m of erium-doped fibre, 200 m of passive, low birefringence spun fibre, a fibre pigtailed polariser (FP), both supplied by York Fibres Ltd, a pigtailed polarisation-insensitive optical isolator (OI) from BT&D Technology and two sets of polarisation controllers (PC's) one placed before the FP and one before the OI. These serve as the means to control Ω and θ and thus control the total loss of the system. Output coupling was provided by a 90:10 coupler as shown. The active fibre had an erbium dopant concentration of 800 ppm, NA=0.15 and a cutoff wavelength of $\lambda_c=960$ nm. The passive fibre was characterized by an NA of 0.1, a cutoff wavelength of $\lambda_c=1250$ nm and a group velocity dispersion parameter of $D=17$ ps/nm km @ 1.56 μm.

The laser exhibited a cw threshold of 25 mW launched pump power. After appropriate adjustment of the PC's, self-starting mode-locking could be initiated by increasing the launched pump power to a "second" threshold value of 80 mW. Figures 4a, b show the cw and mode-locked optical spectra respectively. When running cw, the optical spectrum of the laser exhibited a number of equally spaced peaks. This is a consequence of eq. (3) which indicates a wavelength-dependent cavity loss with period $\Delta\lambda=\lambda L_{b0}/L$. It is believed that the isolator leads (which are made of polarisation maintaining fibre) were the dominant source of birefringence in our cavity and provided for the 1 nm peak spacing in the optical spectrum. When the laser was mode-locked, the peaks disappeared and a broad (>10 nm) lasing linewidth resulted. With intracavity pulse powers in the region of 40 W, there was no evidence in the optical spectrum of self-modulational instability [9] or stimulated Raman scattering. Figure 5 shows the dependence of the pulsewidth on pump power for a particular arrangement of the PC's. The pump power values (in descending order) are 850, 450 and 250 mW, leading to pulse durations of 7, 4 and 2 ns respectively as shown. The square pulse shape is indicative of a switching level similar to that observed in the mode-locked Sagnac loop lasers [1,2]. By careful adjustment of the PC's with the pump power kept at a fixed level, this switching level (and hence

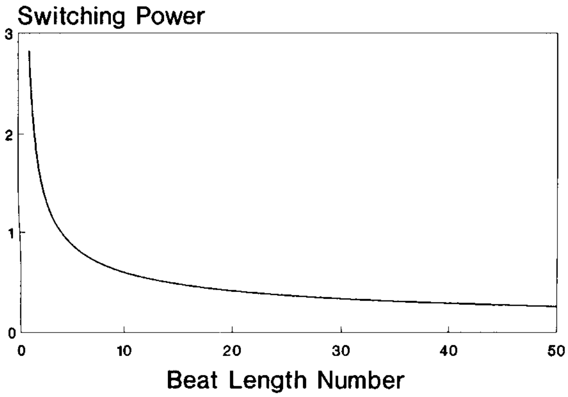

Fig. 3. Normalised switching power p_{sw} versus beat length number (eq. (8)).

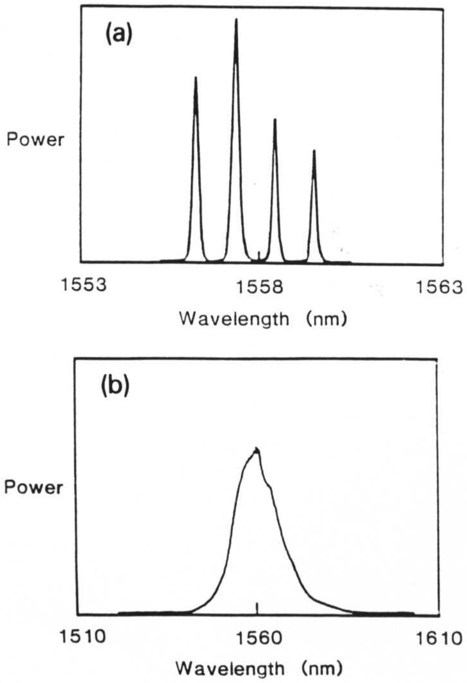

Fig. 4. (a) cw and (b) mode-locked spectra of the 200 m fibre ring laser.

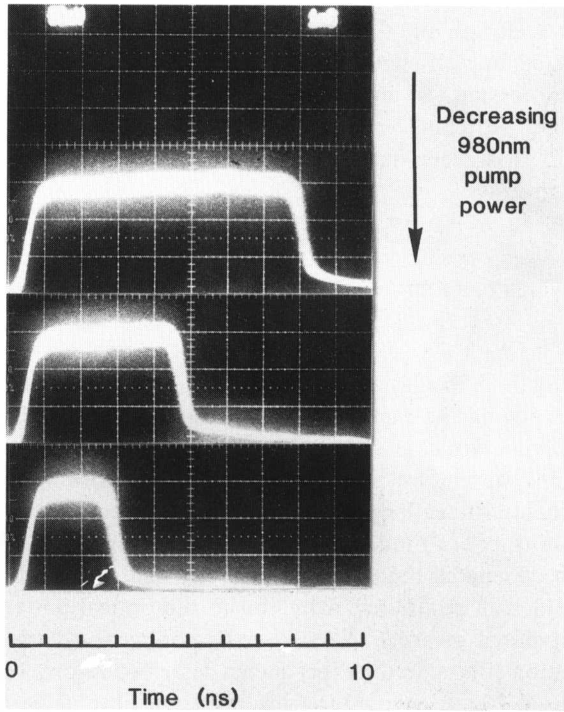

Fig. 5. Pulsewidth dependence on pump power of the 200 m mode-locked fibre ring laser.

the intracavity pulse power) could be made to vary between 20–40 W with an associated variation on pulsewidth of 4–2 ns respectively. Mode-locking could be sustained at a minimum launched power of 79 mW, indicating minimal hysteresis in the mode-locking behaviour.

Replacing the 200 m of low-bi fibre with 3 km of standard telecommunications fibre ($\lambda_c = 1201$ nm, NA$=0.11$, $D = 18$ ps/nm km @ 1.55 μm) resulted in a less stable mode-locked behaviour. The mode-locked threshold, pulse repetition rate, shape, duration and optical spectrum were all very sensitive to the setting of the PC's. The laser could either operate at the fundamental, as seen in fig. 6a, or higher harmonics of the fundamental round trip frequency. The pulse duration varied between 300 ns for the fundamental repetition rate and 0.75 ns at the highest repetition rate observed. Pulse bunching and pulse break-up effects were also observed as seen in figs. 6b, c, indicating a departure from the pure mode-locked behaviour. Typical values for the cw lasing and mode-locking thresholds, which, as with the 200 m fibre, were dependent on the PC's orientation, were 32 mW and 700 mW of launched pump power respectively, but, once mode-locked, the pulses could be sustained at a much lower pump level (80 mW). This hysteresis effect was not observed in the experiments with the 200 m fibre. For launched pump power greater than 750 mW we observed broad (150 nm) laser oscillation, with the harmonically mode-locked laser producing pulses of 2 ns duration at repetition rate of 2.2 MHz, which is the 33rd harmonic of the cavity (see figs. 7,8). The pulse power was 6.8 W which is above the threshold power for stimulated Raman scattering for our fibre which was calculated to be 1.5 W. The broad, Raman shifted lasing linewidth is indicative of a solitary wave formation process [10] and is currently under investigation. Since the insertion loss of the FP in the region of 1600–1700 nm is considerably higher (1–2 dB respectively) than that at 1500 nm (0.24 dB), even broader lasing linewidths than 150 nm should be possible with a different polarising intracavity element.

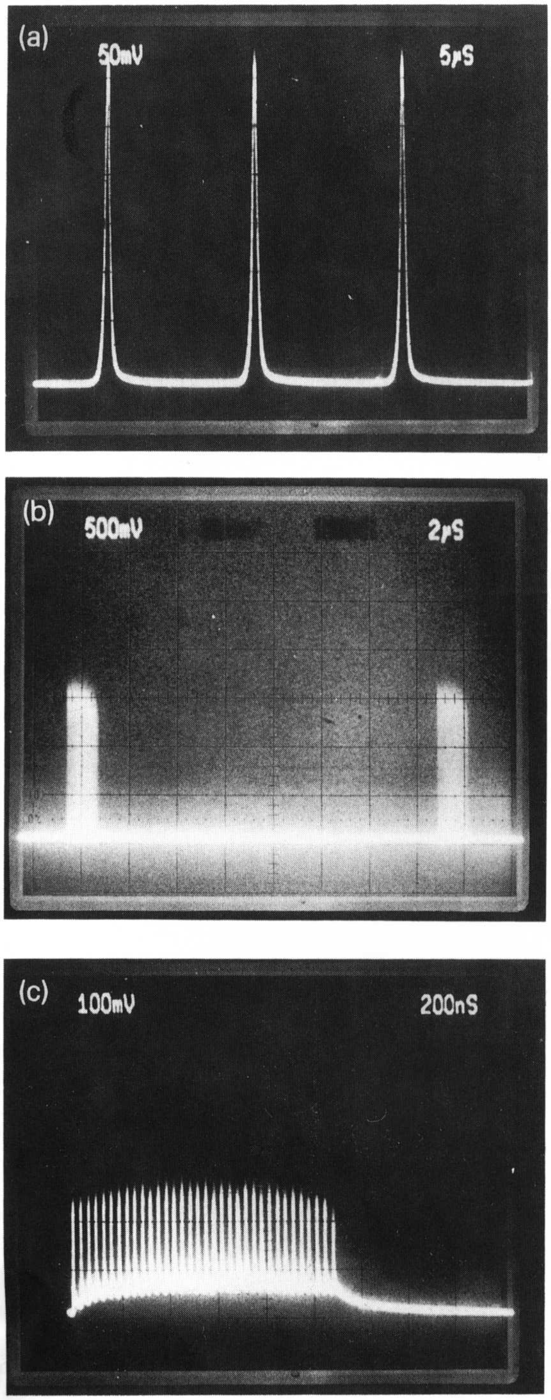

Fig. 6. The 3 km fibre ring laser: (a) Fundamental mode-locking. (b) Pulse bunches circulating around cavity at the round trip frequency. (c) Exploded view of individual bunch.

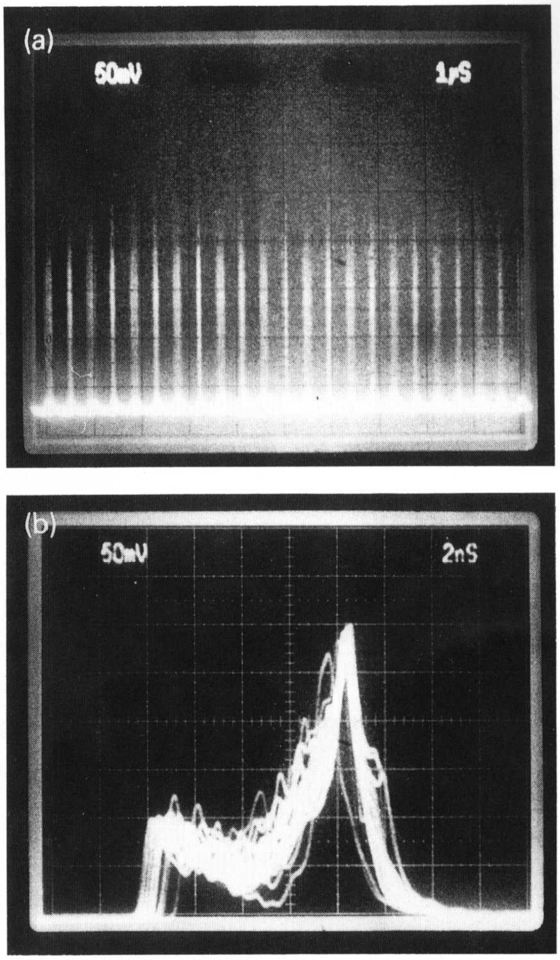

Fig. 7. The 3 km fibre ring laser. (a) 33rd harmonic mode-locking when the lasing linewidth was 150 nm. (b) View of individual pulse.

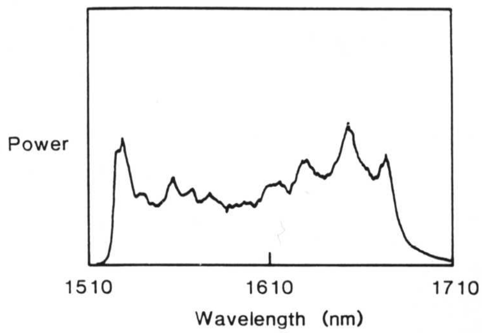

Fig. 8. Optical spectrum of pulses in fig. 7.

4. Conclusions

We have demonstrated that nonlinear birefringence effects can be used in the multibeatlength regime to produce self-starting passive mode-locking in a 200 m EDFL ring cavity. The pulses obtained have a predominately square shape and are in the nanosecond regime. A fibre ring laser mode-locked in this manner provides a convenient optical generator of square pulses appropriate for many fibre optic sensors, including multiplexed discrete sensor configurations and distributed temperature systems. Increasing the cavity length to 3 km has enabled stimulated Raman scattering to produce oscillating linewidths as broad as 150 nm.

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